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PRESSURES AND TEMPERATURES IN PRECAMBRIAN METAMORPHIC ROCKS

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Model *P-T* estimates from nearly 100 Precambrian rocks have been derived by comparing published descriptions of metamorphic mineral assemblages to a standard set of mineral stability data. Pressures, temperatures and metamorphic geotherms show large variations. Nevertheless, model *P-T* data reveal two distinct secular trends. Average metamorphic geotherms have declined through time, and average metamorphic pressures have increased through time. Metamorphic geotherms and pressures from Archean rocks average 54°C/km and 4.1 kbar, respectively. Corresponding figures for early Proterozoic terranes are 47°C/km and 4.3 kbar, and for late Proterozoic terranes 35°C/km and 6 kbar. These secular trends may reflect gradual cooling and thickening of the earth's crust, at least in orogenic belts. There are exceptions to both trends, found in localities where mineral assemblages indicate high pressures (6–12 kbar) and low metamorphic geotherms (20–30°C/km). These assemblages formed in Archean crust that, at least locally, was thicker than 20 km during metamorphism.

1. Introduction

The earth's total radioactivity, and thus total heat production, has declined through time [1–4], implying that global heat flux must have been higher in the Precambrian than it is today. The tectonic response of the early earth to this high heat flow is unknown. Elevated heat flux could have caused high crustal geotherms and extensive melting of the lower crust, resulting in a thin, laterally widespread continental shell [5–7]. Alternatively, high heat flux might have been dissipated by faster generation and cooling of oceanic lithosphere, without affecting heat flow through continental crust [8–10]. This suggests the possibility of thick, stable early Precambrian crust.

Metamorphic mineral assemblages preserve evidence of ancient crustal *P-T* conditions, frozen into a rock at or near the peak of metamorphism. These *P-T* data allow estimation of Precambrian metamorphic geotherms, defined as metamorphic temperatures divided by metamorphic depths. They also set a minimum limit on the thickness of crust during metamorphism. Such data could place useful constraints on models of Precambrian tectonics.

Previous studies of Precambrian metamorphism have considered limited geographic areas [11–14] or else have reported only a small number of *P-T* estimates [9,15]. These studies have used different criteria to evaluate metamorphic pressures and temperatures. Consequently, they have reached markedly differing conclusions. Several studies [11–13] suggest that Archean metamorphic rocks formed primarily at low pressures and moderate to high temperatures, with abundant andalusite and sillimanite. Phanerozoic metamorphic rocks formed mostly at higher pressures, with blueschists and abundant kyanite. Proterozoic rocks fall in between. Other studies [9,14,15] present evidence suggesting that Archean metamorphic conditions and crustal thickness were quite similar to values observed in present-day crust.

This paper presents a review of Precambrian regional metamorphic conditions. Rocks described here come from all continents, although most data are from Africa, Europe and North America. Ages of metamorphism range from 1000 to over 3000 m.y.

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Pressures and temperatures have been derived from descriptions, obtained from the published literature, of 100 metamorphic mineral assemblages. Each assemblage has been compared to a model set of experimental mineral-stability curves. The result is an internally consistent collection of *P-T* estimates. This approach permits direct comparison of metamorphic conditions at different localities, in rocks of varying age.

2. Methods

Metamorphic pressures and temperatures were evaluated by comparing mineral assemblages to a model petrogenetic grid constructed from currently available experimental data. Sources of mineral stability data are Holdaway [16], Al_2SiO_5 minerals; Greenwood [17] and Schreyer [18], numerous mineral stability curves; Hoschek [19], minimum *P, T* stability of chloritoid + quartz and low-*T* stability of staurolite + biotite + quartz; Hess [20], equilibrium conditions of staurolite + chlorite + muscovite = biotite + aluminum silicate; Winkler [21] and Touret [22], hornblende stability; and Holdaway and Lee [23], garnet-cordierite equilibrium. *P-T* conditions for garnet-cordierite assemblages were not estimated unless the Mg content of garnet or cordierite could be established.

Over 90% of the *P-T* data reported here are based solely on this petrogenetic grid. In a small number of cases, it was possible to constrain metamorphic pressures and temperatures more tightly by using mineral-pair geothermometers and geobarometers. Several metamorphic pressures were calculated using the sphalerite geobarometer of Scott and Barnes [24], which seems to give results consistent with silicate stability [25,26], or using the garnet-kyanite-plagioclase-quartz geobarometer [27]. A few temperatures were estimated from garnet-biotite, magnetite-ilmenite and calcite-dolomite geothermometry. Fluid inclusion data, combined with mineral stability, resulted in one *P-T* estimate [28]. A single garnet-clinopyroxene assemblage was evaluated according to the method of Wood [29]. Pressures and temperatures derived using these methods yielded results consistent with the basic petrogenetic grid in each case.

Mineral assemblages were assumed to represent equilibrium unless obvious signs of disequilibrium were noted in the original reference. Water pressure was assumed to equal total pressure unless petrologic evidence dictated otherwise, except in granulite facies rocks. Effects of trace elements on mineral stability curves were ignored, primarily because mineral analyses are not available for most rocks described here. Because of these assumptions, data discussed in the following sections may contain small relative errors. However, these errors are likely to be insignificant compared to the overall range of reported *P-T* conditions. Furthermore, because all assemblages were placed within a specific petrogenetic grid, at least *relative* values of *P* and *T* may be accepted.

3. Data

From the extensive literature describing Precambrian metamorphic rocks, descriptions of approximately 2000 mineral assemblages were examined and compared to the model petrogenetic grid. Nearly 100 assemblages met the following criteria: (1) each mineral assemblage formed in a regional metamorphic event; (2) each defines *P* and *T* to within ±1.5 kbar and ±90°C; (3) the approximate age of metamorphism is known; and (4) rocks were metamorphosed prior to 1000 m.y. ago. Well over half these assemblages constrain *P* and *T* to ±1 kbar, ±50°C. Tables listing assemblages, localities and estimated *P-T* conditions are available from the author.

Fig. 1 presents the metamorphic data in a series of *P-T* diagrams, each keyed to the approximate age of metamorphism. Thirty-seven *P-T* estimates come from rocks metamorphosed over 2500 m.y. ago. Pressures indicated by these Archean metamorphic rocks range from 1 to 13 kbar, at temperatures from 425 to 930°C (Fig. 1a). Corresponding metamorphic geotherms, calculated from the midpoint of each estimated *P-T* range, assuming 3.3 km/kbar, vary between 29 and 95°C/km. High geotherms, in excess of 70°C/km, are not restricted to granulite facies rocks but occur commonly in amphibolite facies rocks. Likewise, there is no apparent correlation between low metamorphic geotherms and metamorphic grade.

Thirty-six *P-T* estimates come from areas metamorphosed between 1500 and 2500 m.y. ago. Because there are few primary metamorphic ages in the range

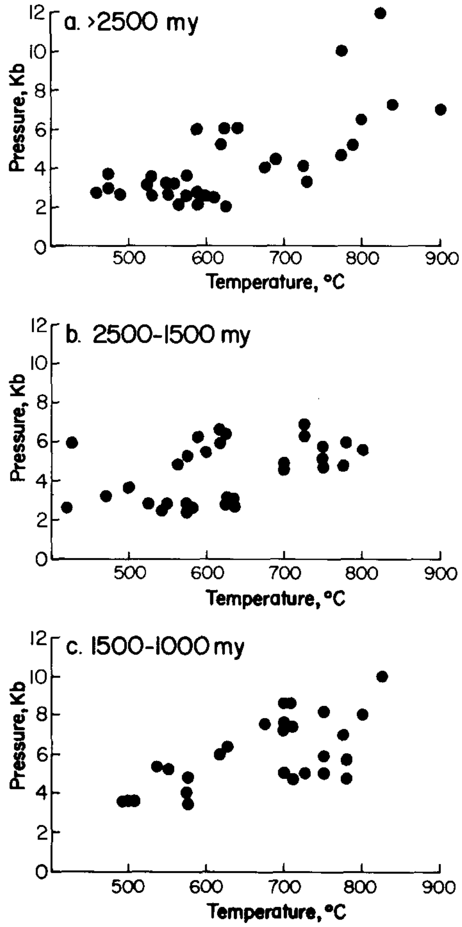

Fig. 1. *P-T* estimates from Precambrian metamorphic rocks, divided according to age of metamorphism. Data points represent midpoints of estimated pressure and temperature ranges.

2000–2500 m.y., most of these are from areas metamorphosed between 1500 and 2000 m.y. ago. Early to middle Proterozoic rocks show pressures of 1.5 to 8.5 kbar, temperatures from 350 to 875°C, and metamorphic geotherms from 21 to 77°C/km (Fig. 1b).

Rocks metamorphosed in the period 1000–1500 m.y. ago are represented by 27 data points (Fig. 1c). About 80% of these come from the Grenville Province of eastern North America. This age grouping therefore has the poorest geographical distribution. Rocks record pressures from 3 to 11.5 kbar, temperatures from 500 to 900°C and metamorphic geotherms from 24 to 50°C/km.

The following discussion assumes that these *P-T* data are representative of Precambrian metamorphic conditions. Additional data may necessitate revision of some interpretations. For example, Kratz and Glebovitsky [30] refer repeatedly to "high-pressure" rocks from Precambrian shields of the Soviet Union, but list no mineral assemblages and very few isotopic ages. If these "high-pressure" rocks proved to be Archean, they would profoundly affect interpretations discussed below.

4. Discussion

Within all age groupings, rocks preserve a wide range of metamorphic geotherms. There are no data to support the interpretation that Archean metamorphism (over 2500 m.y. ago) was primarily of an intermediate *P-T* type [15]. The data also argue against the interpretation that Archean metamorphism was entirely of a low-pressure type [11,12]. Instead, Archean metamorphic geotherms vary from 21 to 95°C/km, and Proterozoic geotherms show nearly as large a variation.

The extent of this variation is similar to that recorded in Phanerozoic metamorphic belts, where regional metamorphic geotherms vary from less than 10°C/km to nearly 100°C/km [31, p. 359]. The only major difference between Precambrian and Phanerozoic metamorphic conditions seems to be the absence of extremely low gradients, or blueschist metamorphism, in pre-1000-m.y.-old rocks [31].

Phanerozoic metamorphic conditions do not reflect processes operating in stable continental crust. Given the large variation in Precambrian metamorphic geotherms, it seems unlikely that Precambrian metamorphic conditions represent *P-T* values of stable Precambrian crust.

Nevertheless, the data reveal a distinct secular trend: on the average, metamorphic geotherms have decreased through time. Fig. 2, a series of histograms plotting the distribution of metamorphic geotherms as a function of age, shows this trend clearly. High metamorphic geotherms are relatively common in Archean rocks but become less common in younger rocks. For example, a metamorphic geotherm of 40°C/km marks the division between kyanite-sillimanite and andalusite-sillimanite metamorphism [16]. Over 75% of Archean metamorphic geotherms fall

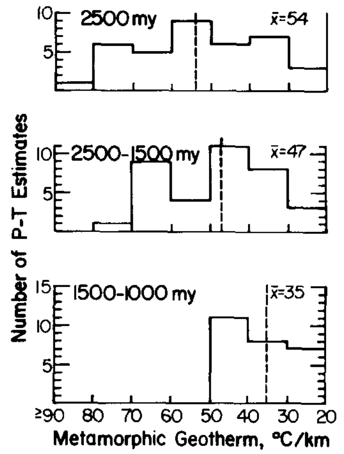

Fig. 2. Histograms showing distribution of metamorphic geotherms within age brackets considered in this paper.

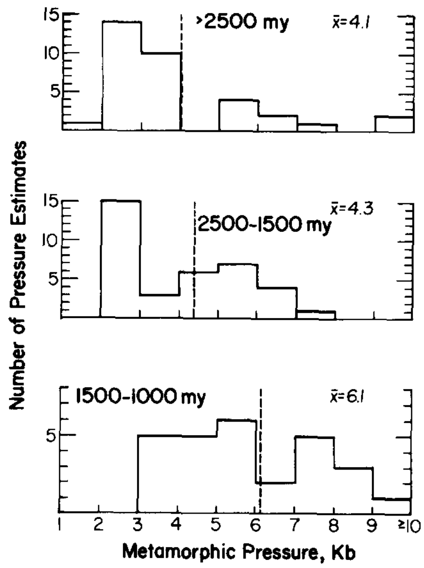

Fig. 3. Histograms showing distribution of metamorphic pressures at various times in the Precambrian. Pressure estimates taken from middle of estimated pressure ranges.

above 40°C/km. Sixty-nine percent of metamorphic geotherms in early to middle Proterozoic rocks fall above 40°C/km as do 41% of metamorphic geotherms in younger Proterozoic rocks. Physical conditions necessary for kyanite-sillimanite metamorphism apparently were more common in the late Proterozoic than in the Archean. This conclusion agrees with observations made by Saggerson [12] and Fyfe [33], that kyanite is more common in Proterozoic rocks than it is in Archean rocks.

Minimum metamorphic geotherms remained constant at roughly 20°C/km throughout the 2500-m.y. period considered in this study (Fig. 2). The observed secular trend reflects a gradual decline in maximum preserved geotherms, from 95°C/km in the Archean, to 77°C/km in the early Proterozoic, to 50°C/km in the later Proterozoic. As a result, the total variability of preserved metamorphic geotherms decreases through time. Average geotherms, calculated for each age group using all data, fall from 54°C/km in Archean rocks, to 47°C/km in early Proterozoic rocks, to 35°C/km in later Proterozoic rocks.

A second secular trend is indicated by metamorphic pressures (Fig. 3). High pressures tend to be more common in younger terrains. If pressures above 6 kbar are classified as "high", then high-pressure metamorphism is indicated by 14% of Archean data, 33% of early Proterozoic data and 48% of late Proterozoic data. Average pressures, calculated using all data, increase from 4.1 kbar in Archean rocks, to 4.3 kbar in early Proterozoic rocks, to 6.1 kbar in late Proterozoic rocks. Older metamorphic rocks tend to be less deeply eroded than younger rocks, a situation opposite to that which might intuitively be expected.

Metamorphic pressures define the minimum possible thickness of the earth's crust during a metamorphic event. The pressure is a measure of how much overburden has been removed, by erosion or otherwise, since the time of metamorphism. Because of isostatic considerations, it is possible that pressures indicated by exposed rocks are proportional to crustal thickness during metamorphism. If this is true, then the secular trend indicated by metamorphic pressures may correlate with gradual thickening of the earth's crust.

However, high metamorphic pressures are not limited to young rocks. Several Archean localities preserve evidence for pressures as high as 6–12 kbar, indicating burial depths of 20–40 km. These include the Scourian gneisses of Harris and Lewis, Scotland, where orthopyroxene-clinopyroxene, clinopyroxene-garnet and garnet–kyanite–K-feldspar assemblages coexist [29,34]. High-pressure assemblages show that, at least locally, pre-2500-m.y.-old crust was thicker than 20–40 km during metamorphism.

The data seem to indicate a correlation between metamorphic pressures and metamorphic geotherms. All extremely high-pressure rocks ($P > 8$ kbar) were metamorphosed at low metamorphic geotherms, 20–30°C/km. Rocks metamorphosed at higher geotherms show lower pressures. A possible interpretation is that crustal thickness was controlled by the geothermal gradient in areas undergoing metamorphism, with the base of the crust being a melting isotherm, as proposed by Fyfe [5] and Hargraves [7]. Crust would be thin in areas of high heat flow but could be much thicker in areas of lower heat flow. A second possibility is that different metamorphic geotherms and pressures might have resulted from different tectonic regimes, perhaps analogous to paired metamorphic belts [35]. Low-geotherms, high-pressure Archean rocks could be early Precambrian equivalents of blueschists, with more common high-geotherm rocks representing Archean equivalents of high-grade metamorphic belts.

Two changes in metamorphic patterns may indicate a significant change in tectonic behavior of the earth in late Proterozoic time. First, maximum metamorphic geotherms decline gradually throughout the Precambrian (Fig. 2), but then increase to 100°C/km in several Phanerozoic metamorphic belts [31]. Second, minimum metamorphic geotherms fall from 20°C/km, where they apparently remained for 2500 m.y. (Fig. 2), to values less than 10°C/km in late Proterozoic blueschist terrains [31, p. 366; 30,32,36]. An interesting speculation is that these changes could signify the beginnings of the modern plate tectonic regime.

5. Conclusions

Any model of Precambrian crustal evolution must satisfy five constraints which are required by the metamorphic *P-T* data.

(1) Metamorphic geotherms show a secular decline.

(2) Metamorphic pressures show a gradual secular increase.

(3) Several Archean localities indicate that, at least locally, early crust was thicker than 20–40 km during metamorphism.

(4) Archean metamorphic geotherms show a large degree of variability, Proterozoic slightly less so.

(5) The total range of metamorphic geotherms indicated by Precambrian rocks decreases through time, primarily because of a secular decrease in maximum preserved geotherms.

No currently accepted model of crustal evolution satisfies all five constraints. Items (1) and (2) are predicted by models of Fyfe [5,6] and Hargraves [7], but these models do not readily account for the presence of low Archean metamorphic geotherms, nor for Archean localities that show 6–12 kbar pressures, without invoking some form of compressional tectonism. More uniformitarian early-earth models proposed by Burke and Kidd [8], Bickle [9] and Windley [10] predict constraints (3) and (4) but fail to account for the others. Perhaps a combination of these two types of model is closer to the truth.

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